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MATERIALS RESEARCH LABORATORIES

MELBOURNE, VICTORIA

REPORT

MRL-R-833

SLOW SPEED MACHINING OF TITANIUM

D.M. Turley

Approved for Public Release

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16. ABSTRACT (if this is security classified, the announcement of this report will be similarly [illegible]

Catastrophic-shear type chips are produced in machining titanium. These are shown to be formed by a cyclic process of indentation and catastrophic shear. The deformation within the chip was very heterogeneous most of the deformation occurring in narrow shear bands between the segments. A model of chip formation has been proposed based on orthogonal planing and machining in the scanning electron microscope. Cracking was often associated with the shear bands and this degraded surface finish. The change to a continuous chip at low cutting speeds reported by Recht was not observed and furthermore, the surface finish further deteriorated. Decreasing the depth of cut, rake angle, or using tools having a large nose radius made the chip less segmented and consequently improved surface finish. The depth of deformation beneath the machined surfaces increased with increasing depth of act and decreasing rake angle. Machining with a lubricant decreased the depth of deformation.

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SLOW SPEED MACHINING OF TITANIUM

INTRODUCTION

Titanium and its alloys are being increasingly used in the aerospace industry, because of their high strength/weight ratio and excellent corrosion resistance. Their mechanism of chip formation is different than for most other materials [1-4]. The deformation or strain within the chip is very heterogeneous, intense shear being concentrated in widely separated shear bands so dividing the chip into distinct segments. This chip is possibly best described as a catastrophic-shear chip [5] and most investigators [1-3] attribute its formation to the adiabatic conditions which are presumed to occur during catastrophic shear because of titanium's low specific heat and low thermal conductivity. Specifically, because of the low specific heat, when catastrophic shear occurs it is generally concluded that there is an appreciable rise in temperature within the shear band. This rise in temperature induces strain softening which results in a further concentration of shear in this region, and the low thermal conductivity further aids this process by restricting the amount of heat conducted out of the shear band. In this regard Recht [2] has concluded that for a particular metal or alloy the strain softening effect depends upon cutting speed, high cutting speeds favouring strain softening and catastrophic-shear chips. For mild steel, Recht reported that the transition from continuous to catastrophic-shear chips occurred at 7 m/s, whereas for titanium because of its low specific heat and thermal conductivity it occurred at $\sim 5 \times 10^{-3}$ m/s. More recently it has been concluded that, when machining titanium [6,7] or a Ti-6Al-4V alloy [4], the formation of each segment of the chip can be divided into two stages, namely, indentation of the cutting tool into the workpiece followed by catastrophic shear.

These laboratories have become involved in the machining of titanium and titanium alloys for the following reasons. Firstly, as part of a co-operative programme between Australia, England and the USA, attention has been focussed on the role of surface integrity on the fatigue properties of these materials. Secondly, part of the offset work expected to be undertaken by Australian industry associated with the purchase of the new tactical fighter will involve the machining of titanium and titanium alloys. As there is little practical experience in machining these materials in Australia, there

will therefore be a need to provide relevant scientific support to industry. To establish a comparative basis, considerable effort has been directed initially to machining titanium at slow speeds, and results detailing the nature of the chip formation process and its attendant affects on surface integrity are presented in the report.

EXPERIMENTAL PROCEDURE

The titanium was a commercial grade in the mill-annealed condition, in the form of 16 mm thick plate. Specimens 50 mm long x 4.7 mm wide x 16 mm deep were extracted from the plate. The machining operation was orthogonal planing, all specimens being cut in the longitudinal direction. Machining was done with high speed steel tools of various rake angles with a 5° clearance angle, and the cutting speeds investigated ranged downwards from 2.5×10^{-2} m/s to 7×10^{-5} m/s. Machining forces were measured on a quartz multi-component dynamometer (Kistler), and unless otherwise stated cutting was done dry. For lubricated cutting a neat cutting oil was used (Cutmax 570). Machining was also carried out at low cutting speeds 1.7×10^{-4} m/s - 1.7×10^{-5} m/s within a scanning electron microscope (SEM). This technique [8] enabled the machining operation to be observed directly and to be video-recorded for replaying.

Metallographic sections were prepared by first cutting the chip out of the workpiece and plating it, usually with nickel, to ensure good edge retention. The chip was then mounted in araldite and the metallographic preparation procedure was as follows:

1. Abrade on SiC papers finishing on a well worn 1200P grade.

2. Polish with 4-8 μm diamond paste on a napless cloth for ~ 5 minutes.

3. Polish with a chromic acid - Linde B alumina mixture consisting of 30 ml of 20% chromic acid in distilled water, 40 gm Linde B and 200 ml of distilled water, for ~ 3-5 minutes.

4. Removing the passivation film produced by (3) by polishing with Linde B alumina with distilled water for 3-5 minutes.

5. Etching by swabbing with Kellers reagent (5 ml HNO_3, 3 ml HCl, 2 ml HF, and 190 ml distilled water).

The primary function of each of the polishing stages (2) and (3) was to remove the surface damage produced by the preceding stage.

RESULTS AND DISCUSSION

A. Nature of the Chip Formation Process

A titanium chip produced by cutting in air and viewed from the side in the SEM is shown in Fig. 1. Distorted segments can be seen, where one segment is in the process of being formed. A crack (arrowed Fig. 1) can also be seen running from the cutting edge of the tool towards the free surface. These cracks often ran below the level of the cutting edge where they had a very detrimental effect on surface finish and this aspect will be discussed later. The chip formation process shown in Fig. 1 appears to be discontinuous, with each segment being separated by complete fracture. However, this is only an edge effect due to the plane stress conditions existing there. An optical micrograph of a longitudinal section through the mid-section of a chip similar to that of Fig. 1 is shown in Fig. 2. Here, plane strain conditions exist and fracture, when it does occur between the segments, is not complete and the segments remain together. It is apparent from Fig. 2 that the deformation within each segment is not very large; instead the deformation is concentrated between the segments in very narrow shear bands. This catastrophic-shear chip is similar to a discontinuous chip [9,11], except that fracture between the segments is not complete. From examination of these longitudinal sections together with studies of the machining process in the SEM it has been possible to develop a model for chip formation, which is described in the following.

A.1 Model of Chip Formation

The chip formation process is illustrated diagrammatically in Fig. 3, and description of the basic steps involved in the formation of a segment in relation to Figs. 3(a)-(d) is as follows:

(a) Catastrophic shear is about to occur along A'B, and a crack AA' has propagated from the cutting edge down into the workpiece and then back up towards the uncut surface. If the segment ABCD had not undergone any plastic deformation its shape would be ABED. With reference to Fig. 2 it is apparent that no part of the free surface of the chip is parallel to the uncut surface, i.e. BH. However, the free segment surfaces corresponding to BC are all parallel, thus indicating that all segments undergo the same amount of shear. This type of deformation has been defined as "homogeneous shear" [7] and the homogeneous shear strain is given by:

$$\gamma_h = \frac{EC}{CG}$$

where EC is the shear displacement and CG is the thickness of the segment. From Fig. 2 EC and CG can be measured, from which $\gamma_h \sim 1.3$. Since the free segment surfaces in Fig. 2 corresponding to BC are all parallel, γ_h is the same for all segments.

(b) After catastrophic shear occurs along A'B, the cutting tool advances and passes over that part of the crack which was below the cutting edge leaving it in the machined surface. The cutting tool then begins to indent into the shear band A'B.

(c) The cutting tool continues to advance and the shear band becomes bent down towards the cutting edge and the new segment being formed begins to bulge against the rake face of the tool. The shear bands associated with the previously formed segments also continue to be bent down towards the cutting edge. Homogeneous shear occurs as this new segment begins to form.

(d) The cutting tool continues to advance. The shear band is now further bent closer to the cutting tool down towards the cutting edge. A new shear band first propagates down from the cutting edge of the tool then briefly parallel to the cutting direction before turning up and propagating towards the uncut surface. A crack has formed in this shear band adjacent to the cutting edge of the tool (Fig. 2). Catastrophic shear is about to occur again and the new segment is about to be formed. Homogeneous shear of this new segment is complete, and catastrophic shear along the shear band A'B separating the previously formed segment and the new segment is now also completed. The catastrophic shear strain is given by:

$$\gamma_c = \frac{OF}{t} \quad \text{(refer Fig. 3(d))}$$

From Fig. 2, OF (shear displacement) and t (thickness of shear band) can be measured, from which $\gamma_c \sim 7$. The measurement of a number of shear displacements and the corresponding shear band thicknesses shows that there is some variation in γ_c, $\gamma_c \sim 7$ being a typical value. In all cases however, γ_c is much larger than γ_h.

Since the material in the shear band is subjected to homogeneous shear prior to experiencing catastrophic shear, the total shear strain in the shear band (γ_{SB}) is given by:

$$\gamma_{SB} = \gamma_h + \gamma_c$$

$$\gamma_{SB} \sim 8$$

Hence, it is confirmed that most of the shear occurs during catastrophic shear and that deformation is concentrated in the narrow shear bands. It is interesting to note that it has been previously [6,12] proposed that continuous chip formation also occurs by an indentation-catastrophic shear process, the segments in this case being very much narrower. Furthermore, von Turkovich [12] in his analysis of continuous chip formation developed expressions for γ_h, γ_c and γ_{SB} similar to those developed in the present work. The particular advantage in the present work, however, was that the segments were so large that measurements could be made from micrographs; γ_h and γ_c and γ_{SB} can therefore be determined quantitatively. Other important points in relation to the model of chip formation are described in the following:

A.1.1 Movement up the rake face

As previously reported by Komanduri and von Turkovich [4] the movement up the rake face of the cutting tool of a segment during its formation is similar to a stick-slip process. During the indentation stage of segment formation (Figs. 3(b)-(d)) there is virtually no sliding of the segment up the rake face; instead, the segment bulges against the rake face in what Komanduri and von Turkovich have described as an upsetting process. Once catastrophic shear occurs, however, the newly formed segment moves rapidly in the shear direction and consequently slides up the rake face causing the previously formed segment and the chip to slide up with it. However, it should be noted that sliding of the chip up the rake face is continuous. Even during the indentation stage of segment formation (Figs. 3(b)-(d)) catastrophic shear is still occurring along the shear band separating the previously formed segment from the segment being formed, and consequently, whilst the segment being formed is not sliding the chip is sliding up the rake face though at a slower rate than after catastrophic shear occurs.

A.1.2 Effect of Rake Angle

For chips cut at large negative rake angles (-40°) there was not a large difference between the amount of deformation within the segments and in the shear bands, the deformation within the chip being relatively uniform (Fig. 4). In fact, this chip appears to be between a catastrophic-shear chip and a continuous chip.

A.1.3 Thickness of the Segments

The thickness of the segments increased with increasing depth of cut and decreased with decreasing rake angle as shown in Fig. 5.

A.1.4 Machining Forces

In orthogonal cutting there are only two machining forces to be considered; in the present work the force parallel to the cutting direction has been termed the cutting force and the force normal to the machined surface the reaction force. The cutting force and reaction force trace obtained when machining commercial titanium at +10° rake angle, 125 μm depth of cut and at 5×10^{-4} m/s is shown in Fig. 6. Both the cutting force and reaction force vary cyclically with segment formation, and even though these variations may vary slightly from segment to segment they can be related to the process of chip formation shown diagramatically in Fig. 3. The mode of variation of the cutting force with segment formation to be described was confirmed by measuring the cutting force whilst machining in the scanning electron microscope. In Fig. 3(a) catastrophic shear is just about to occur, and the cutting force at this point is a maximum and corresponds to R in Fig. 6. Once catastrophic shear occurs the cutting force drops rapidly (to S in Fig. 6). From Fig. 6 it can be seen that the reaction force reaches a maximum just after catastrophic shear occurs and then decreases with the

cutting force. The decrease in the reaction force is associated with the movement of the segment (AA'BCD in Fig. 3) up the rake face of the tool once catastrophic shear occurs. Since the coefficient of sliding friction is less than the coefficient of static friction, the frictional force along the rake face decreases and this corresponds to a decrease in the reaction force. As the cutting tool continues to advance, indentation commences and a new segment begins to form, and the cutting force begins to increase whereas the reaction force, which lags behind the cutting force, continues to decrease. When the stage shown in Fig. 3(c) is reached the cutting force has risen appreciably and the reaction force also begins to increase. As indentation further proceeds, both the cutting force and reaction force increase. The segment is of course, stationary, though the shear band becomes displaced against the rake face of the tool. Both the cutting and reaction force continue to increase until the stage is reached in Fig. 3(d), and catastrophic shear is about to occur once more. It is interesting to note that the cutting force generally increases at a constant rate during indentation, which is slower than the rate it decreases once catastrophic shear occurs; on the other hand, variation in the reaction force during segment formation is more symmetrical. The cyclic variation in forces is related to the degree of chip segmentation. Factors that increase the degree of chip segmentation, such as decreasing cutting speed and increasing depth of cut, increase the magnitude of the cyclic variation in forces.

A.1.5 Vibrations of the Cutting Tool

The cyclic variation in the cutting and reaction forces results in the cutting tool elastically deflecting or vibrating during machining. This effect can be observed directly when machining in the SEM, the deflection of the tool relative to a reference pointer being readily discernible (the magnitude of the horizontal deflection was used to measure the cutting force when machining in the SEM [13]). During the formation of a segment the cutting tool does not deflect or vibrate at a constant rate. When catastrophic shear occurs the tool moves forward very quickly corresponding to the drop in cutting force. When re-indentation commences the forward movement is reduced, and as indentation proceeds the tool begins to move slowly backwards until catastrophic shear once more occurs and the tool again moves rapidly forward. There were also vibrations of the cutting tool in the vertical direction associated with the variations in the reaction force, and as will be discussed later these are important with regard to surface finish.

A.1.6 Contact Conditions on Rake Face

Prior to the chip curling it is in close contact with the rake face of the cutting tool. Information on the contact conditions can be ascertained by examining the rake face side of chips produced by interrupted cutting and the rake face of the corresponding cutting tool. A view of the rake face side of the chip at the chip root is shown in Fig. 7. There is a "smooth region" at the chip root, but some distance away there is a region where metal has been removed (designated A in Fig. 7), and from examination of the rake face of the corresponding cutting tool (Fig. 8) it is apparent that this metal has been transferred as build-up to the cutting tool. The corresponding profiles match very closely, for example, the three small holes

arrowed in Fig. 7 are matched by the three corresponding pieces of metal build up arrowed in Fig. 8. Moreover, the cumulative layered nature of the metal build-up can be seen in Fig. 8, where it is also apparent that no metal build-up occurs right at the cutting edge, which corresponds to the "smooth region" on the rake face side of the chip. The region shown in Fig. 7 where metal is transferred from the chip to the cutting tool is where adherence between the chip and tool occurs. The scratch marks or grooves on th· surface of the chip in region A of Fig. 7 are produced by the passage of the chip over the metal build-up on the tool.

These contact conditions are similar to those previously described for continuous chip formation by Doyle et al, [14,15] who carried out orthogonal cutting experiments using transparent sapphire tools which enabled the contact conditions on the rake face to be observed directly. The "smooth region" observed in the present work appears to correspond to what was termed zone 1A where they concluded there was sliding with very little rubbing, and the region of gross transfer of metal to the tool corresponds essentially to what was termed zone 2. A schematic sketch of the tool/chip interactions in the present work is given in Fig. 9. The contact length of the chip on the rake face of the tool, corresponds to the length of zone 1A. The change in chip profile as it passes over the metal build-up on the tool (depicted in Fig. 9) enables the contact length to be readily measured from longitudinal sections of machined specimens (refer Fig. 2). It was found that the contact length increased with increasing depth of cut and with decreasing rake angle, as shown in Fig. 10. Machining with a neat cutting oil decreased the contact length (Fig. 11); the amount of build-up on the cutting tool was also reduced.

B. Surface Integrity

B.1 Surface Finish

The cracking in the shear bands adjacent to the tool cutting edge (see Fig. 2) results in a degradation of surface finish, as remnants of these cracks are left in the new surface. A view of a machined surface is shown in Fig. 12 where rows of cracks can be seen aligned normal to the cutting direction, each row of cracks being associated with the formation of a particular segment. Another undesirable feature of these surfaces was that surface undulations associated with tool vibrations were present, and these are shown more clearly in Fig. 13. The tool vibrations are associated with segment formation, each undulation being produced by the formation of one segment. From studies of the chip formation process in the SEM, it was apparent that during the indentation part of the chip formation cycle (Figs. 3(b)-(d)) the cutting tool penetrated deeper into the workpiece. Once catastrophic shear occurred, the forces on the tool were relieved and the tool lifted up, and the cracks left on the surface (Fig. 1?) often lay on this part on the undulation.

Both the cracks on the surface and the surface undulations were a result of the catastrophic-shear chip. It seems reasonable to conclude therefore that if the catastrophic-shear chip could be changed to a continuous chip then an improvement in surface finish would occur. To this end,

attempts were made to improve the surface finish by altering machining variables and these will now be briefly described.

B.1.1 Effect of Speed

Recht [2] has previously reported that a change from a catastrophic-shear chip to a continuous chip occurs when the cutting speed is reduced to $\sim 5 \times 10^{-3}$ m/s. Attempts in the present work to find this transition were unsuccessful, even though cutting speeds were reduced to as low as 1.7×10^{-5} m/s. Also, contrary to Recht's finding, the chips became more segmented with decreasing cutting speed, and the surface finish further deteriorated. Surfaces produced at cutting speeds of 2.5×10^{-2} and 7×10^{-5} m/s are shown in Figs. 14(a) and (b), respectively. For the slower speed the fracture regions are more numerous and aligned in very pronounced rows.

B.1.2 Other variables

The number of cracks on the surface was substantially reduced if the depth of cut was made very small (5 μm). This improvement in surface finish was associated with a change in the nature of the chips, the chips being less segmented and more continuous. As stated previously, the deformation within the chips was more homogeneous when produced with tools of large negative rake angle. This decrease in degree of segmentation also resulted in an improvement in surface finish, both surface cracks and surface undulations being reduced. Using tools with a large nose radius 0.125-0.250 mm also resulted in an improvement in surface finish. Once again the nature of chip formation was altered, the degree of segmentation being reduced. Machining with a neat cutting oil had little effect on the surface finish, and although the contact length and the amount of metal build-up on the tool was reduced, the nature of the chip formation process remained unaltered.

B.2 Deformed Surface Layers

It has previously been reported [16,17] that two distinct layers of deformation are present beneath machined surfaces. The first layer is at the surface, and is so heavily deformed that its structure is unresolvable by optical microscopy; this has been termed the fragmented layer. Below the fragmented layer is a much deeper less heavily deformed layer in which structural features can be resolved by optical microscopy; this has been termed the deformed layer. The fragmented layer is part of the shear zone which is left beneath the machined surface. In the present work shear bands are bent down towards the cutting edge of the tool, and while a shear band passing from the chip around the cutting edge and into the machined surface is not clearly discernible in Fig. 2, it is readily apparent for chips cut at large negative rake angles (Fig. 15). Moreover, while a fragmented layer (shear band) is not clearly discernible in normal sections of machined surfaces cut at positive rake angle; previous work indicates that a thin fragmented layer would be detected in taper sections [16,17] or by transmission electron microscopy [18]. The presence of a fragmented layer or

shear band at the machined surface indicates that surface strains are very high, as apart from the shear strain $\gamma_{SB}(\gamma_{SB} \sim 8)$, there are additional surface strains due to bending of the shear band around the cutting edge and rubbing of the newly generated machined surface against the clearance face of the tool. A deformed layer containing many twins can be observed in Fig. 16, and was in fact observed in normal sections of all machined surfaces.

The degree of deformation in the deformed layer decreased with increasing depth beneath the surface, the bottom of the deformed layer being taken as the depth at which deformation twins ceased to occur. It has been reported [19] that deformation twins are developed in titanium deformed 5% by cold rolling, and hence the bottom of the deformed layer represents a strain boundary equivalent to < 5% deformation by cold rolling. The summation of both fragmented and deformed layers gives the total depth of deformation and it is this parameter which has been measured in the present work.

The depth of deformation increased with increasing depth of cut and decreasing rake angle as shown in Fig. 17. The depth of deformation did not increase linearly with depth of cut (Fig. 17) nor did it increase linearly with decreasing rake angle (Fig. 18). A nose radius on the cutting tools resulted in an increase in the depth of deformation; the larger the nose radius the greater the depth. Cutting with a neat oil resulted in a decrease in the depth of deformation as shown in Fig. 18. Cutting speed (2.5×10^{-2} - 7×10^{-5} m/s) did not have a significant effect.

CONCLUSIONS

1. The formation of the catastrophic-shear chip could be divided into two main stages. Firstly, there was an indentation stage where the cutting tool pushed into the workpiece, followed by the formation of a shear band and catastrophic shear.

2. The deformation within the chip was very heterogeneous, most of the deformation occurring in narrow shear bands between the segments. The shear strain in the shear bands (γ_{SB}) was much greater than within the segment (γ_h). However, for chips produced at large negative rake angle (-40°) the deformation within the chip was more uniform, and the difference between γ_h and γ_{SB} was not as great.

3. The thickness of the segments increased with increasing depth of cut and decreased with decreasing rake angle.

4. The machining forces varied cyclically with segment formation.

5. The contact length of the chip along the rake face increased with increasing depth of cut and with decreasing rake angle. Machining with a neat cutting oil reduced the contact length.

6. Cracking was often associated with the shear bands, and remnants of these cracks were left on the workpiece surface degrading surface finish.

7. Machining at lower cutting speeds did not result in a change to a continuous chip as reported by Recht. Instead, the chips became even more segmented, cracking became more extensive and the surface finish further degraded.

8. The formation of catastrophic-shear chips at very low cutting speeds (1.7×10^{-5} m/s) indicates that the plastic instability developed in the shear bands may not necessarily be adiabatic shear.

9. Machining at small depths of cut, or with large negative rake angle tools, or with tools having a large nose radius improved surface finish. This improvement was associated with less cracking in the shear bands and a more continuous chip.

10. The depth of deformation beneath the machined surfaces increased with increasing depth of cut and decreasing rake angle. Machining with a neat cutting oil reduced the depth of deformation.

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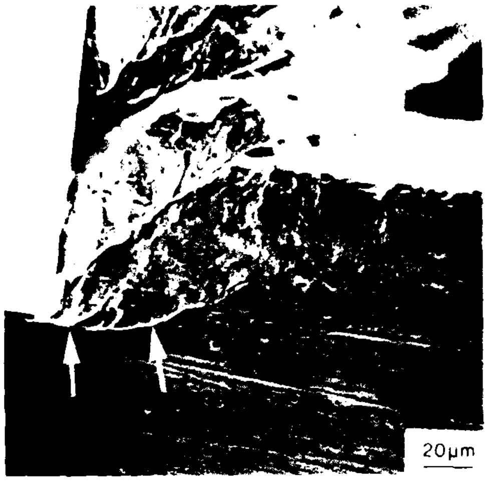

FIG. 1 Scanning electron micrograph of an interrupted cut (in air). Distinct segments are present and a crack (arrowed) can be seen running into the chip adjacent to the cutting edge.

FIG. 2 Optical micrograph of a mid-section of an interrupted cut showing that the deformation is concentrated between the segments in very narrow shear bands. Depth of cut 150 μm, +10° rake angle, cutting speed 2.5×10^{-2} m/s.

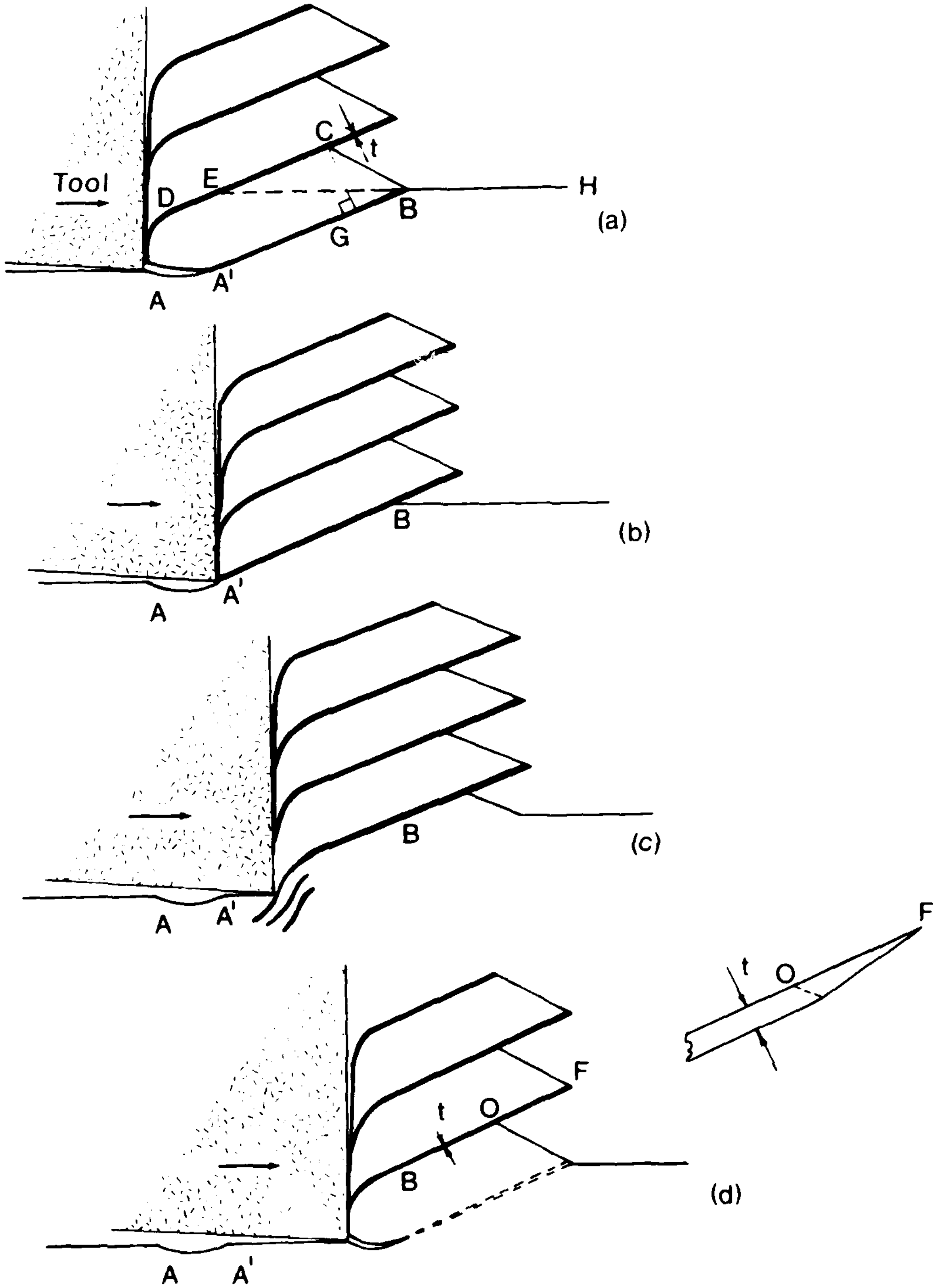

FIG. 3 Diagrammatic illustration of the steps involved in the formation of a segment.

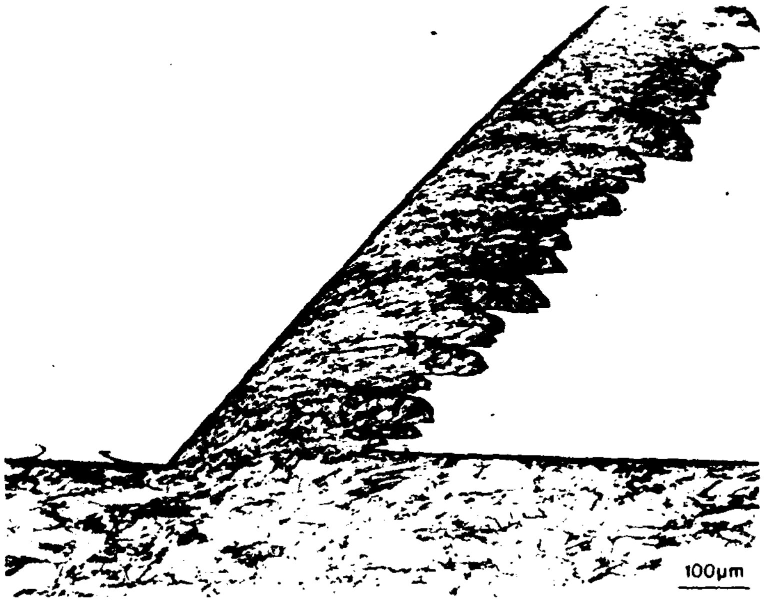

FIG. 4 Optical micrograph of a mid-section of an interrupted cut made with a cutting tool of -40° rake angle. Note that the deformation within the chip is relatively uniform (cf. Fig. 2). Cutting speed 2.5×10^{-2} m/s.

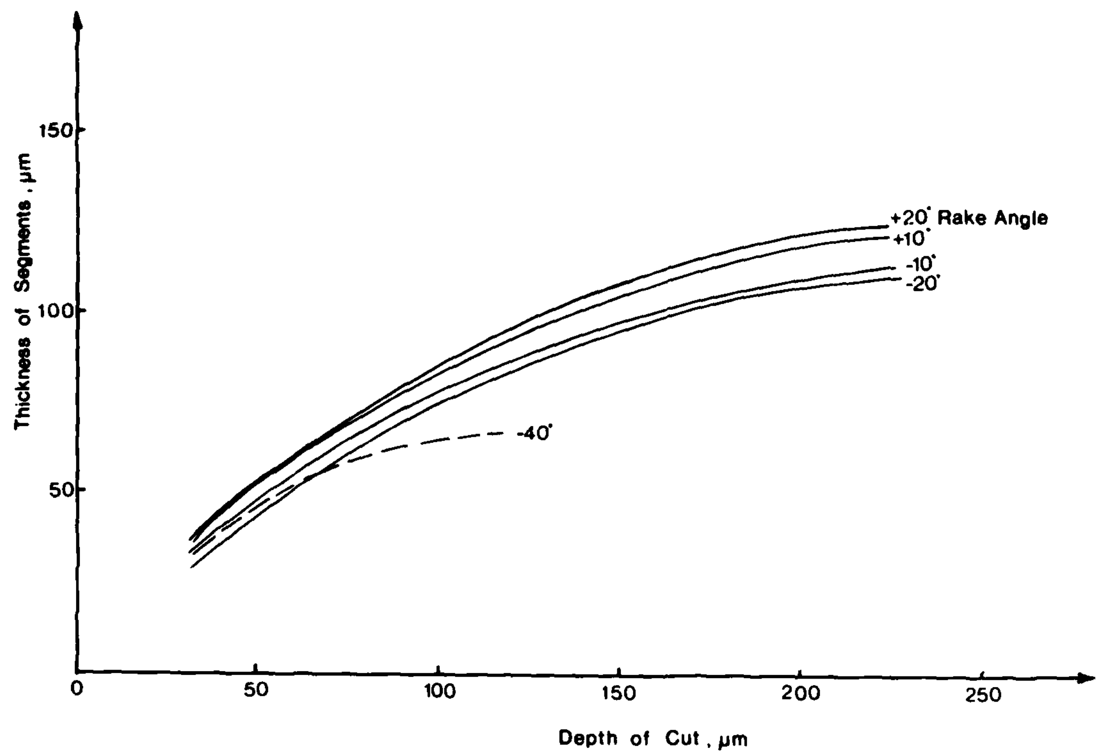

FIG. 5 Relation between thickness of the segments and depth of cut for various rake angles, cutting speed 2.5×10^{-2} m/s.

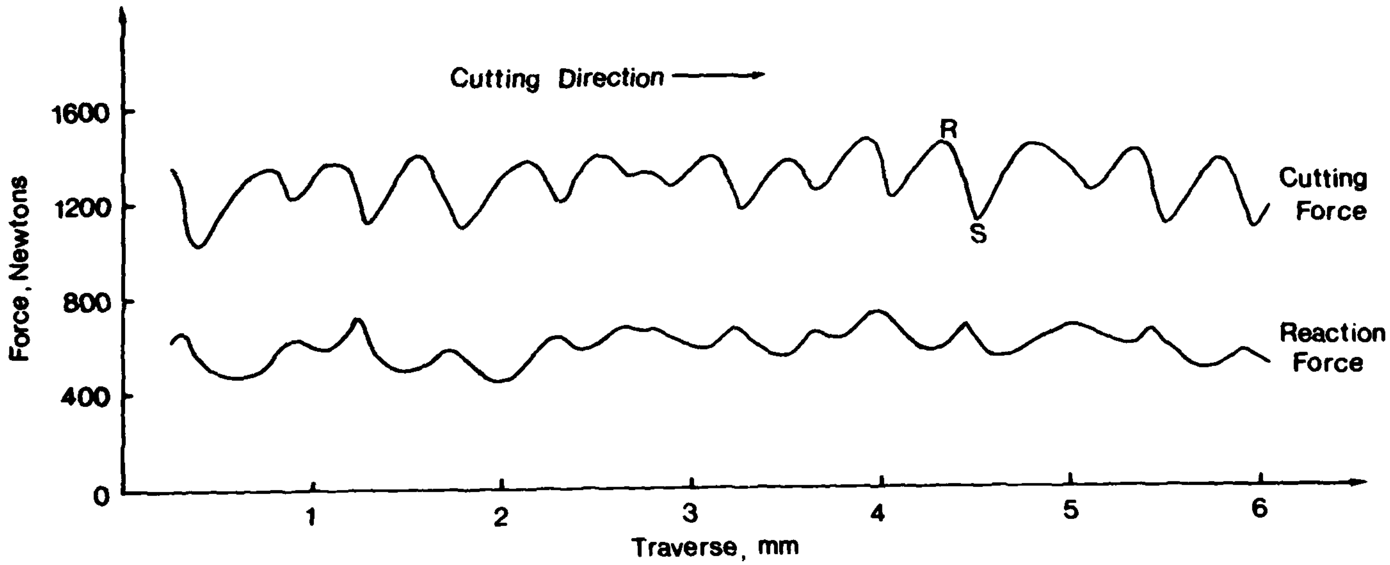

FIG. 6 Cutting force and reaction force traces. Note the cyclic variations. Depth of cut 125 m, +10° rake angle, cutting speed 5 x 10^{-4} m/s.

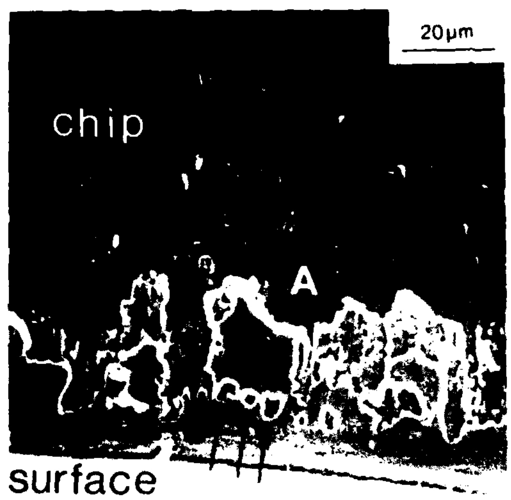

FIG. 7 Scanning electron micrograph at the chip root of the rake face side of a chip. There is a "smooth region" at the chip root in which there are some holes (arrowed) where metal has been removed. Further away from the chip root (region A) metal has been completely removed.

FIG. 8 Scanning electron micrograph of the rake face of the corresponding cutting tool. Note that the metal build-up which consists of cumulative layers does not occur at the cutting edge. Figure 8 matches Fig. 7 very closely and the three small holes arrowed in Fig. 7 correspond to the three pieces of metal build-up arrowed in Fig. 8.

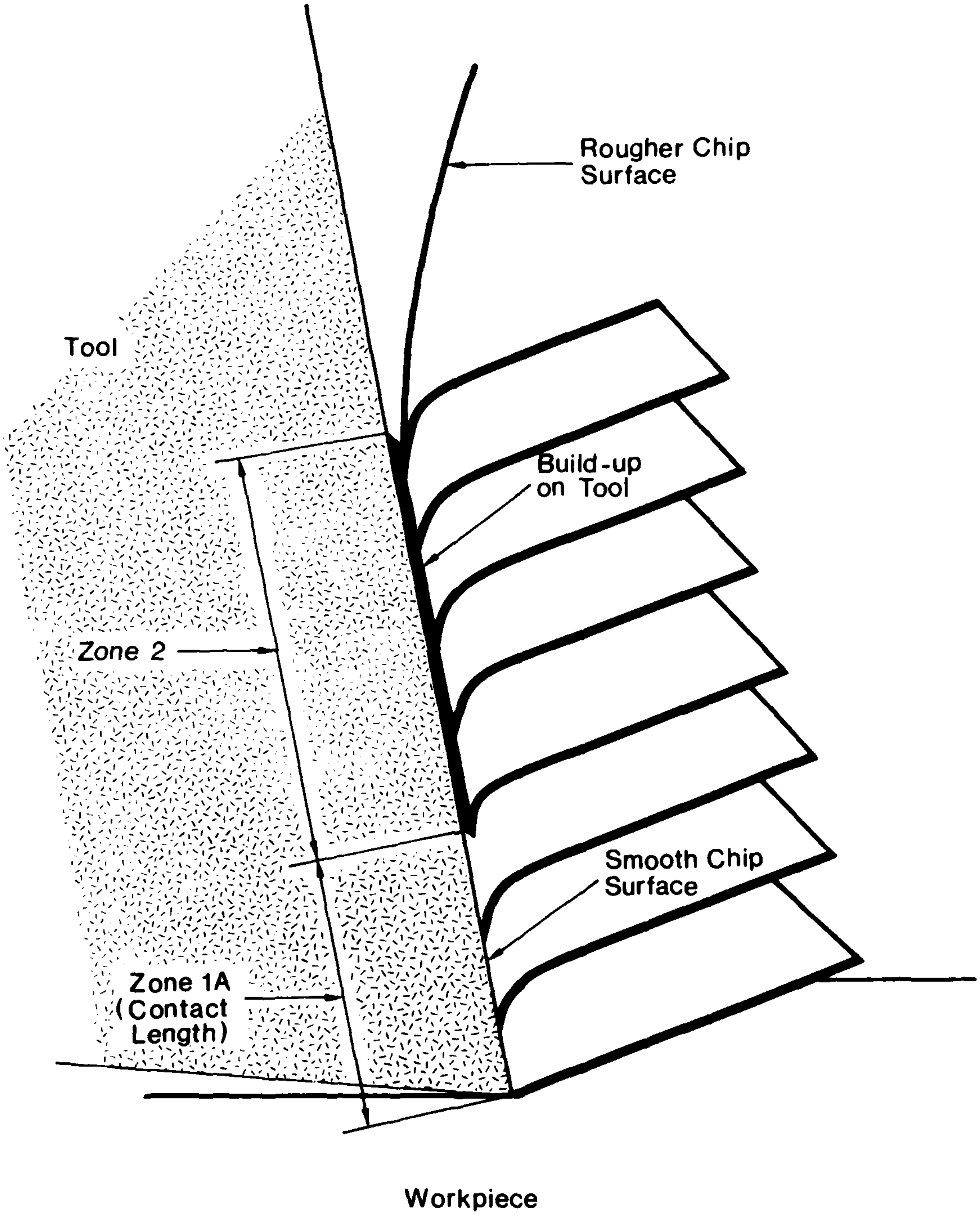

FIG. 9 Schematic sketch of the tool/chip interactions.

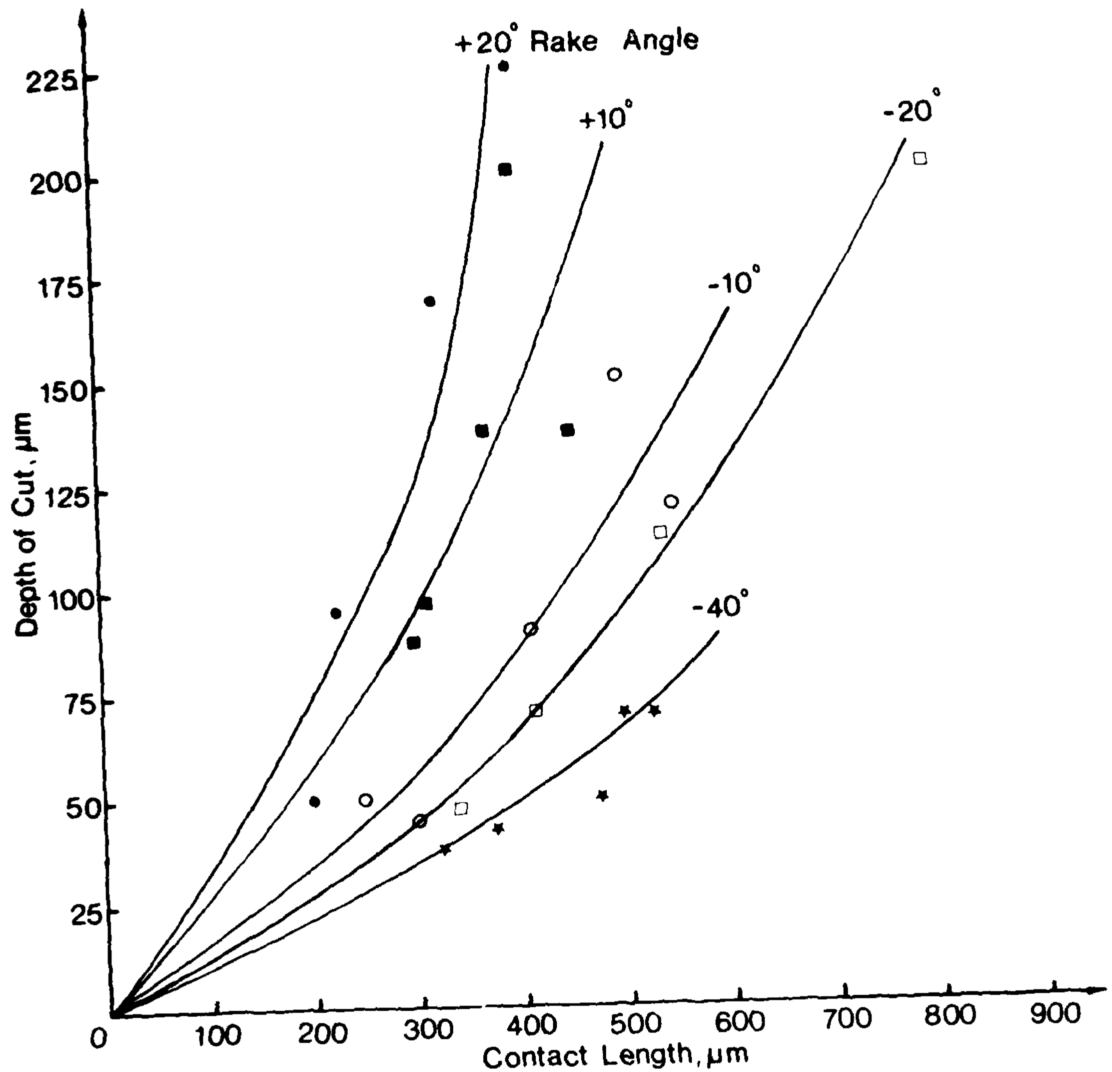

FIG. 10 Relation between depth of cut and contact length for various rake angles, cutting speed 2.5×10^{-2} m/s.

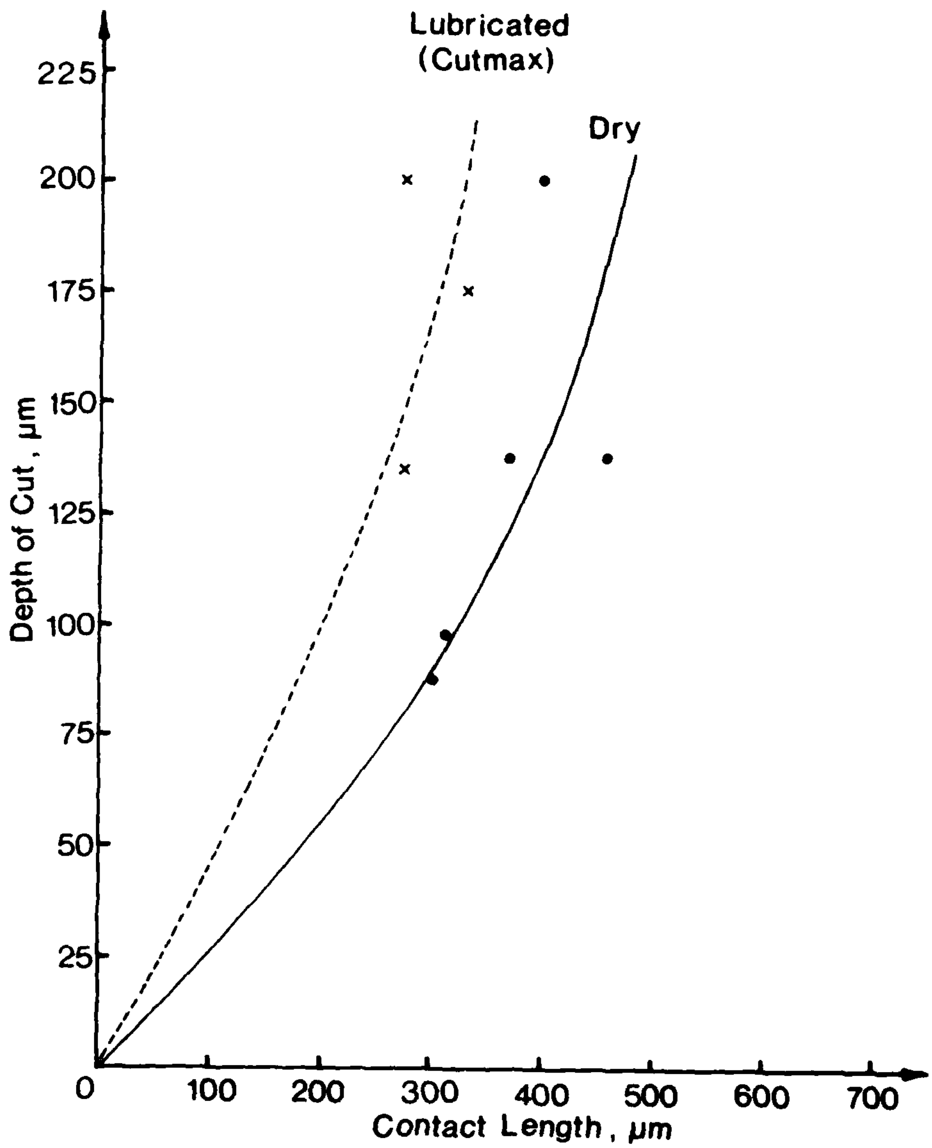

FIG. 11 Effect of machining with a neat cutting oil on the relation between depth of cut and contact length. Rake angle + 10°, cutting speed 2.5 x 10^{-2} m/s.

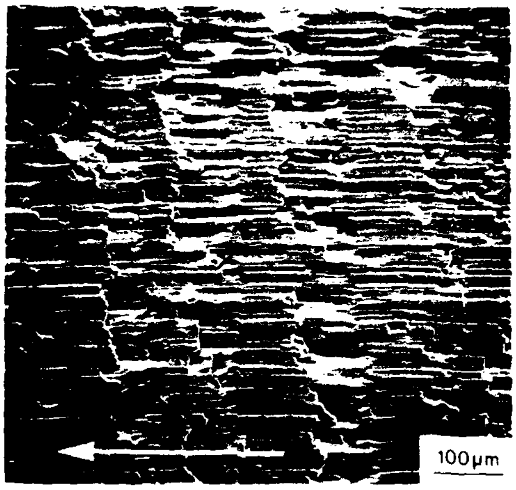

FIG. 12 Scanning electron micrograph of a machined surface showing rows of fracture separated by relatively smooth regions. Depth of cut 125 μm, +10° rake angle. The arrow indicates the direction of cutting.

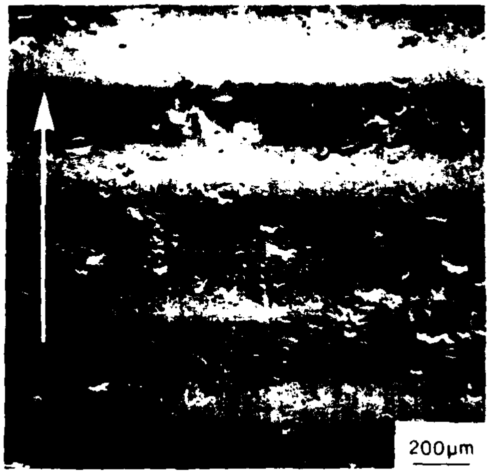

FIG. 13 Scanning electron micrograph of a machined surface showing surface undulations associated with tool vibrations. Depth of cut 125 μm, -10° rake angle, cutting speed 2.5×10^{-2} m/s.
The arrow indicates the direction of cutting.

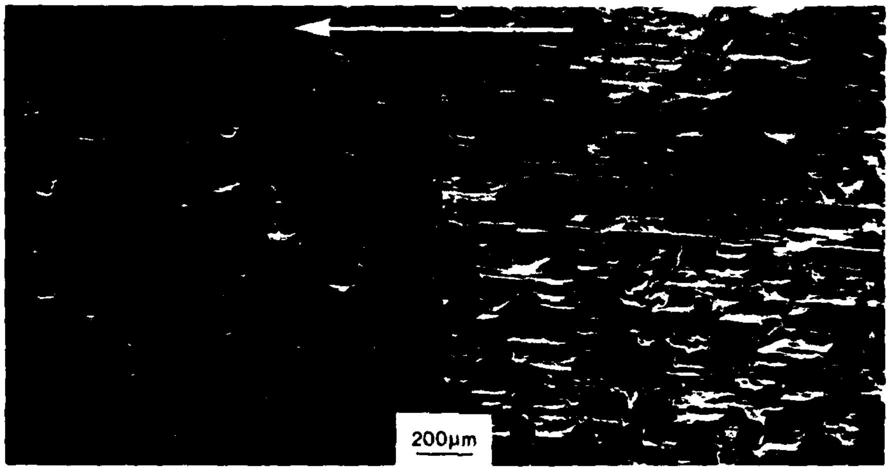

FIG. 14 (a) and (b)

Scanning electron micrographs of machined surfaces produced at cutting speeds of (a) 2.5×10^{-2} m/s and (b) 7×10^{-5} m/s. Note that for the slower speed (b) the fracture regions are more numerous. Depth of cut 50 µm, 0° rake angle. The arrow indicates the direction of cutting.

FIG. 15 Optical micrograph of a mid-section of an interrupted cut. Shear bands in the chip (arrowed) can be seen bending around the cutting edge into the machined surface. Depth of cut 125 μm, -20° rake angle, cutting speed 2.5×10^{-2} m/s.

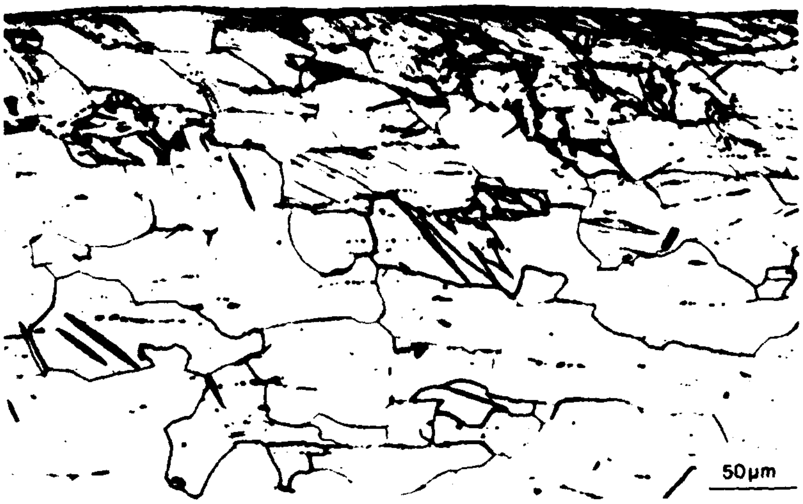

FIG. 16 Optical micrograph of a normal section through a machined surface showing that a deformed layer containing many deformation twins is present. Note the fragmented layer which occurs right at the surface is too shallow in this case to be observed.

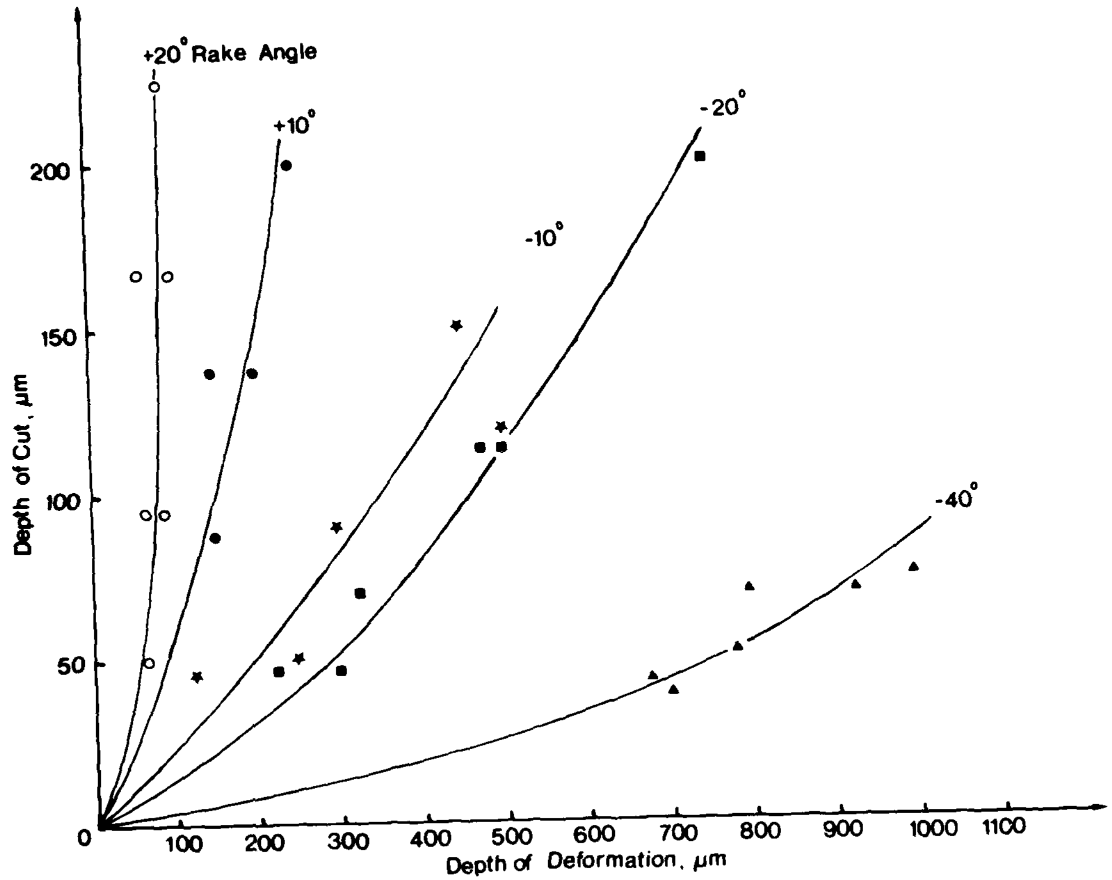

FIG. 17 Relation between depth of cut and depth of deformation for various rake angles, cutting speed 2.5×10^{-2} m/s.

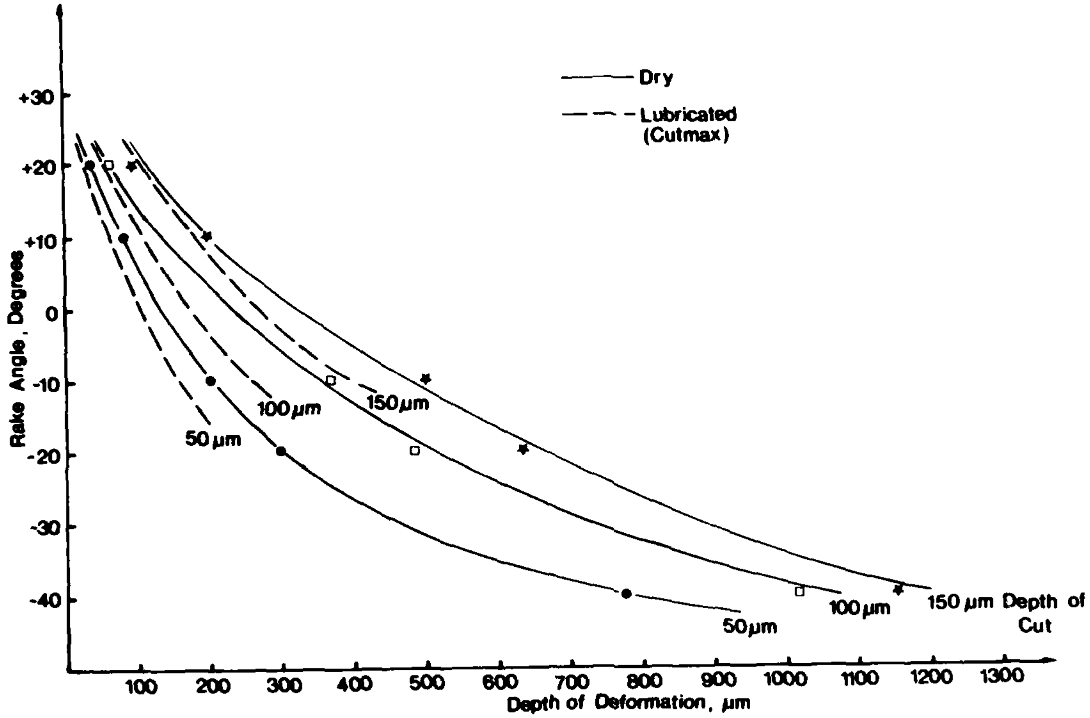

FIG. 18 Relation between rake angle and depth of deformation for various depths of cut, cutting speed 2.5×10^{-2} m/s.

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